The Multi-Dimensional Character and Mechanisms of Core-Collapse Supernovae

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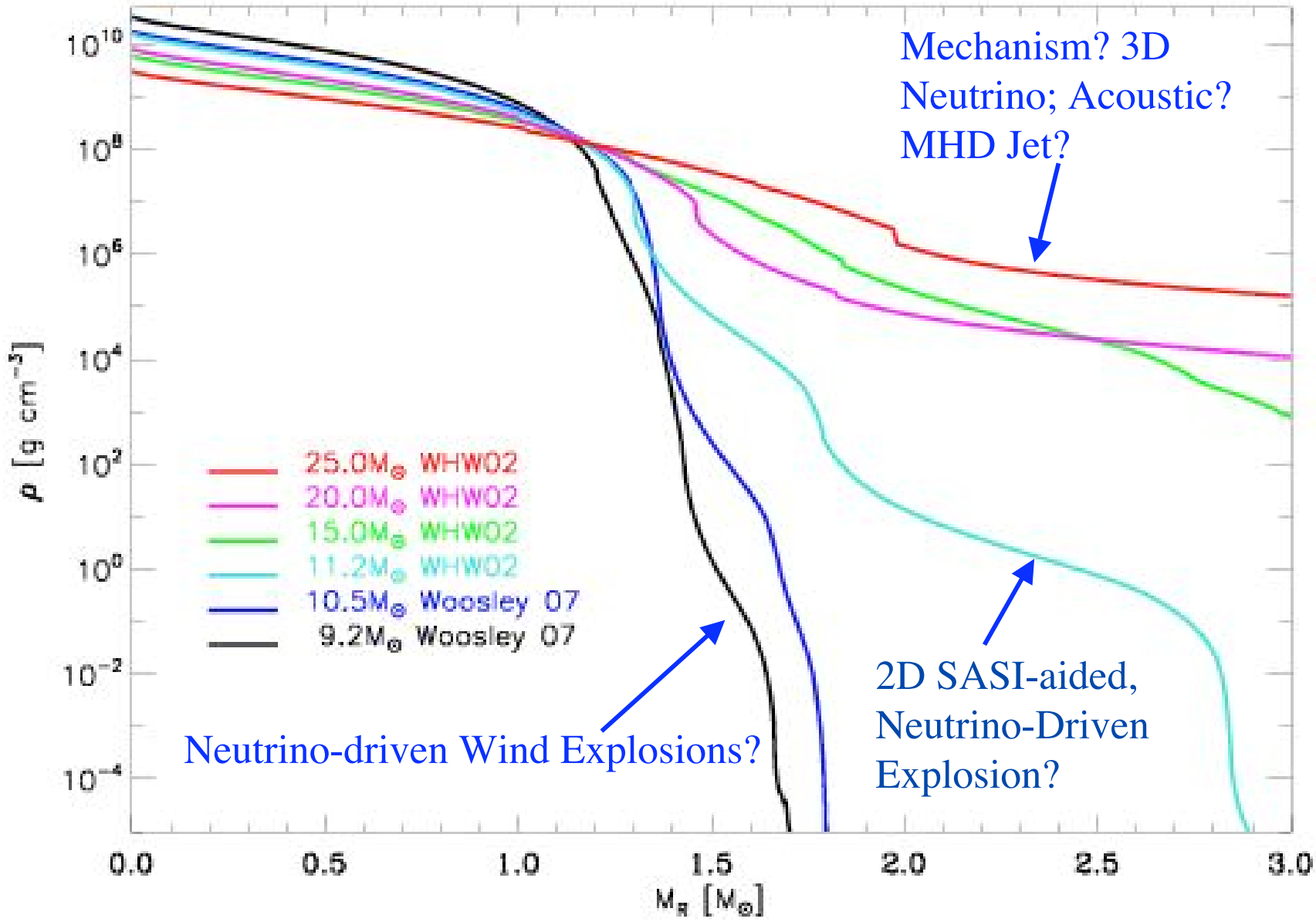
Important Questions in Supernova Theory

- Mechanism of explosion?
- Pulsar Kicks (proper motions)?
- Nucleosynthesis: Nickel, etc. Yields?
- R-process site?
- Blast Morphology (and polarization)?
- Pulsar Spins?
- Pulsar/AXP/Magnetar B-fields?
- Black Hole formation?
- Systematics with progenitor (and role of rotation/magnetic fields)?
- Connection with GRBs and Hypernovae?

Density Profiles of Supernova Progenitor Cores



Mechanisms of Explosion

- Direct Hydrodynamic Mechanism: always fails?
- Neutrino-Driven Wind Mechanism, ~1D (Burrows 1987) Lowest-mass massive stars, ~spherical (e.g., 8.8 solar masses, Kitaura et al. 2006)
- SASI-aided (Blondin et al. 2003) Neutrino-Driven Wind Mechanism, 2D (e.g., 11.2 solar masses, Buras et al. 2006)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf (Dessart et al. 2006)
- Acoustic Power Mechanism (after delay), all progenitors explode (Burrows et al. 2006,2007a)
- Nuclear-burning aided? (Mezzacappa et al. 2006)
- MHD Jet Explosions (e.g., Burrows et al. 2007b)
- The Key feature of almost all mechanisms is the **Breaking of Spherical Symmetry**

Issues/Problems

- Neutrino-driven wind explosions are "under-energetic": ~0.05 to 0.2 Bethes, or don't work (in 2D): What of M > ~12 solar masses?
- 3D effects may be needed to save the day for the neutrino mechanism for most progenitors and to achieve ~1 Bethe energies (last chance?); but note Janka's 15 solar mass model, this meeting ; Better and Multi-D Neutrino Transport?
- Long delay for Core-oscillation/Acoustic mechanism: Does something else precede it? Can the core modes achieve the required amplitudes?
- MHD Jets: Rapid Rotation necessary

Neutrino-Driven Wind Explosions: Low Mass and AIC

8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion

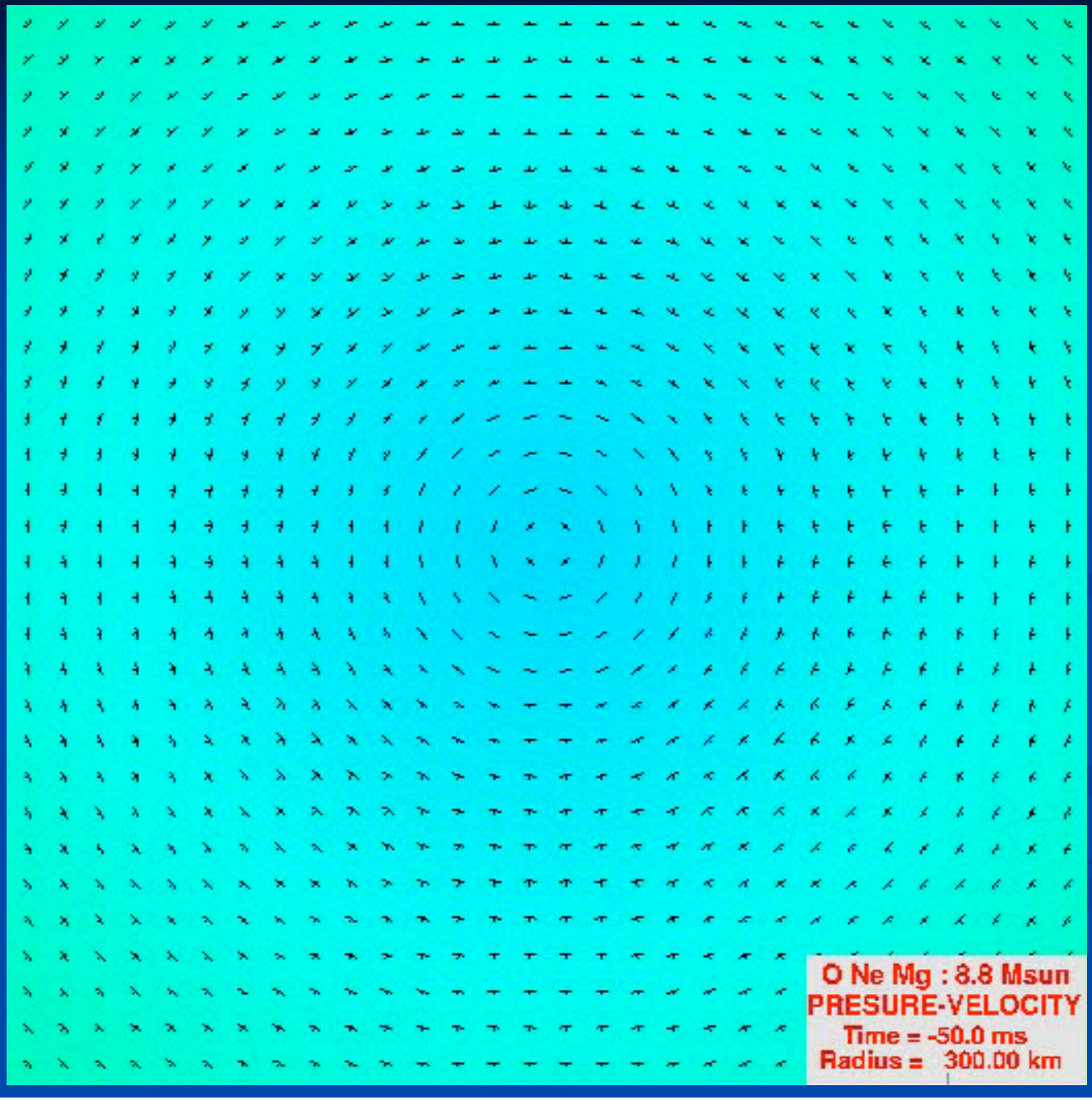
First shown by Kitaura et al. 2006

NOTE WIND THAT FOLLOWS:

TWO SHOCKS!

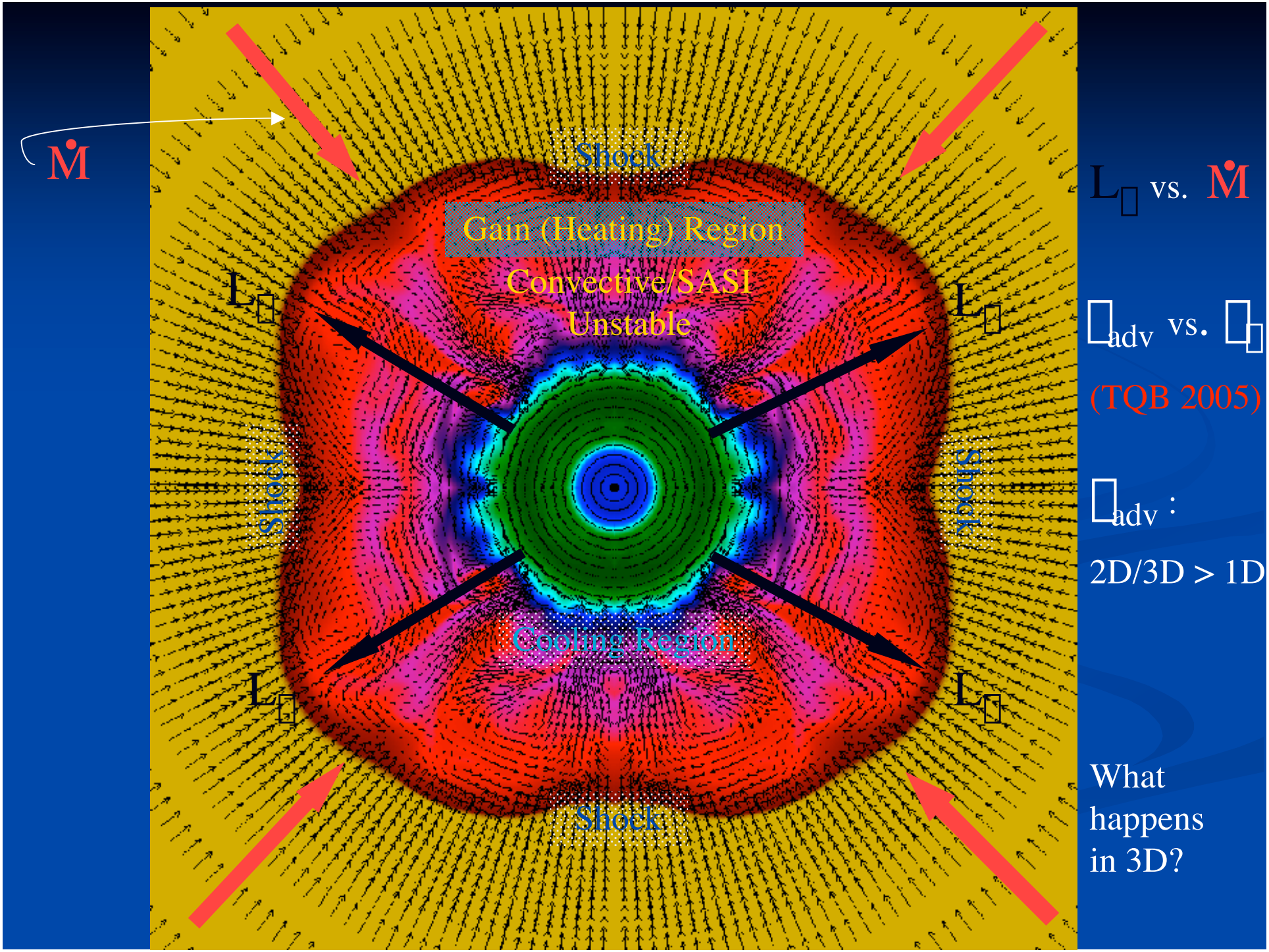
Dessart, Burrows et al. 2007;

Burrows 1987



1) What is the Essence of the Neutrino Mechanism

2) How can it "be made" to work?



L_{ν} vs. $\dot{M}$

τ_{adv} vs. τ_{ν}

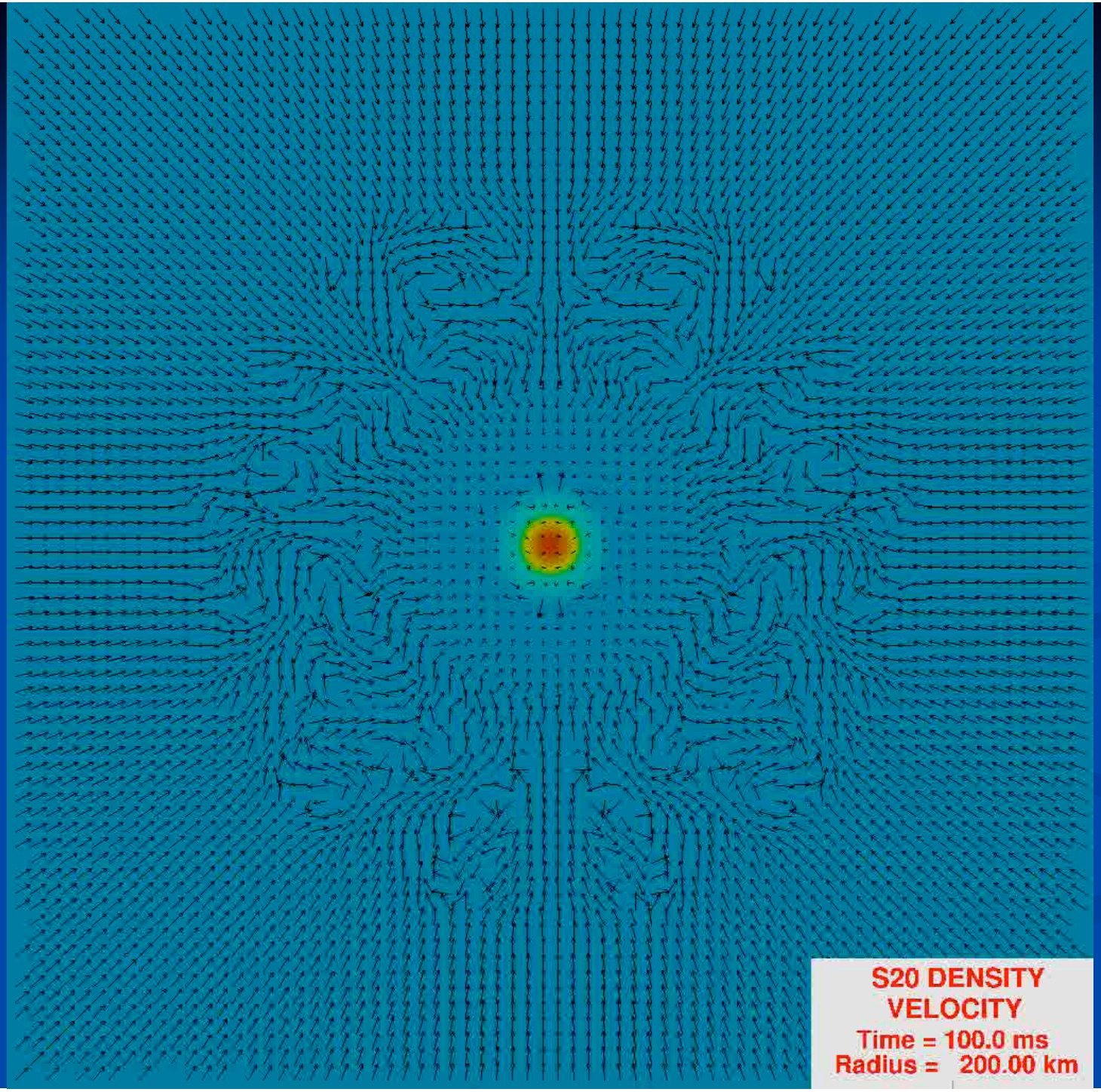
(TQB 2005)

τ_{adv} :

2D/3D > 1D

What happens in 3D?

But,
in
3D?

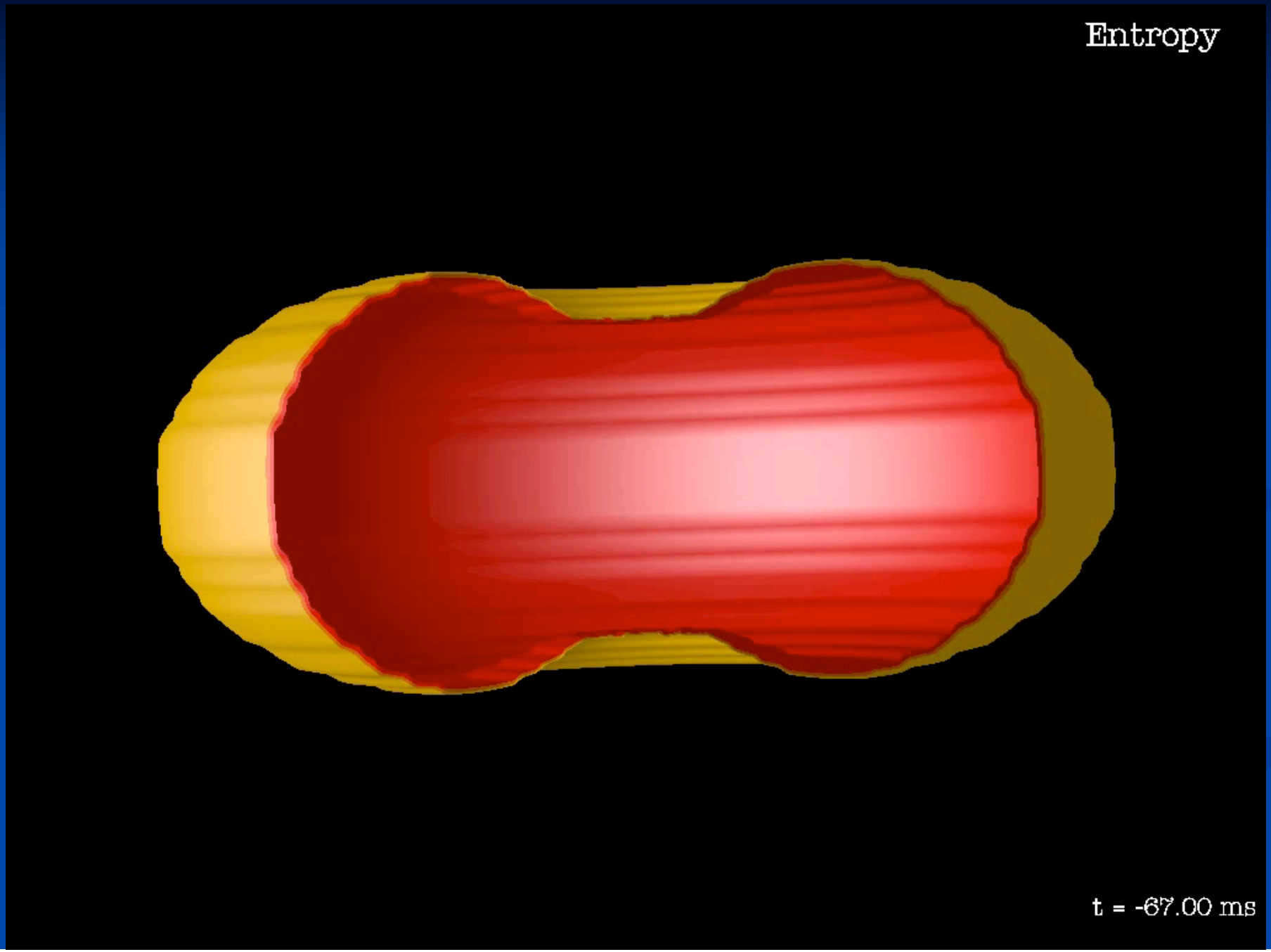


Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

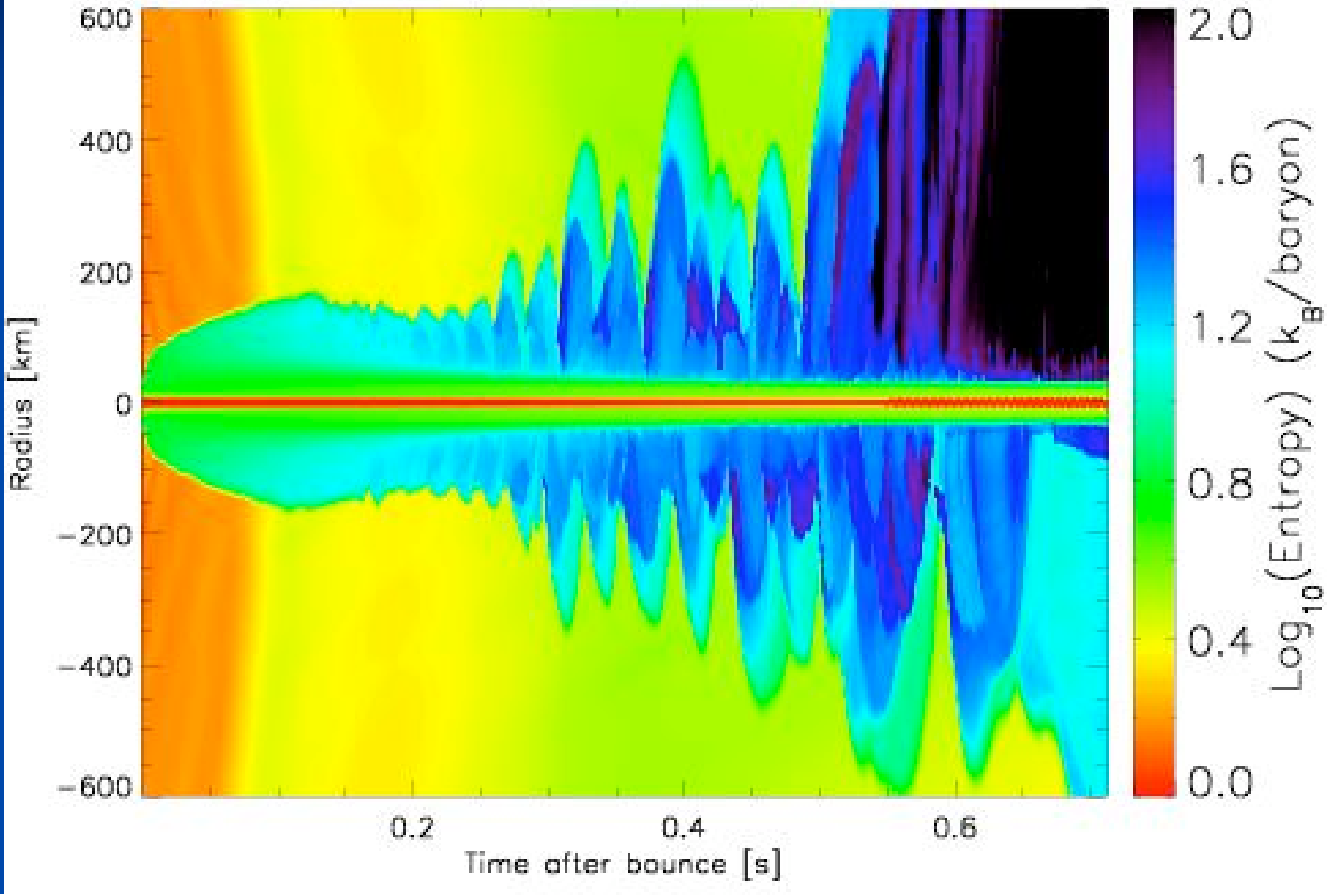
Rapid Rotation!

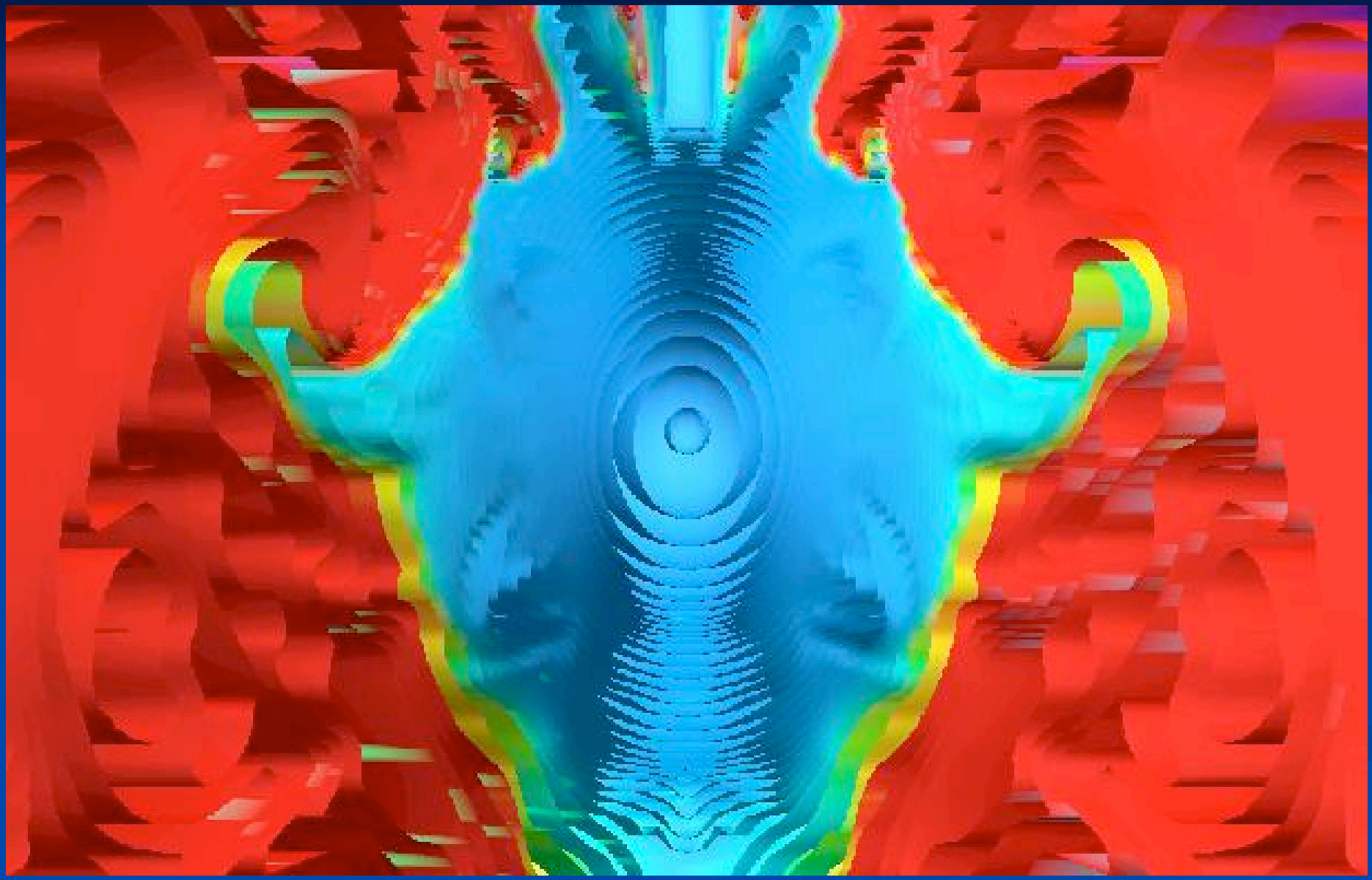
AIC: 1.92 solar masses:



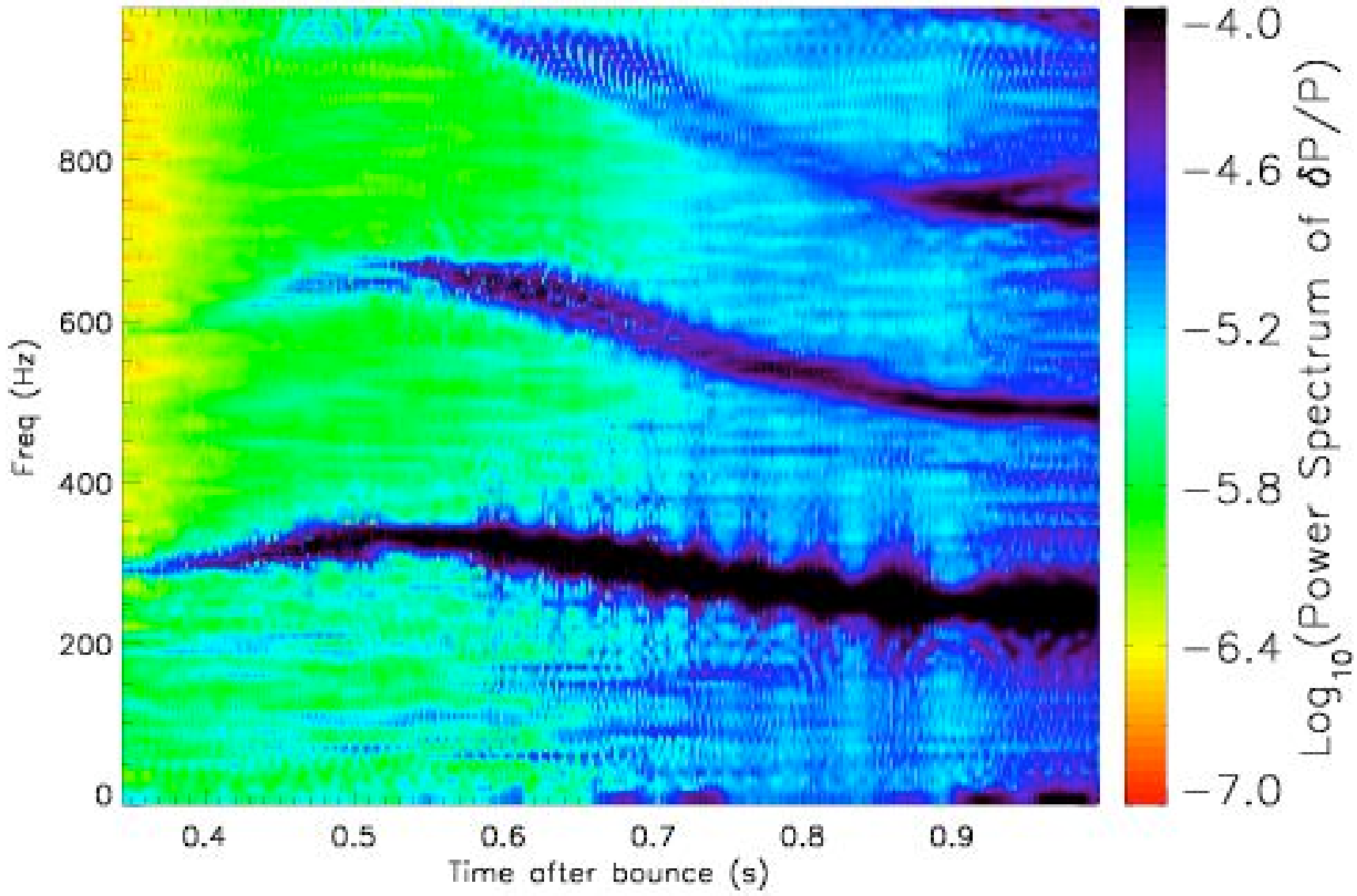
Core Oscillation/Acoustic Power Mechanism

Inner 600-km Look at the Advective-Acoustic Instability

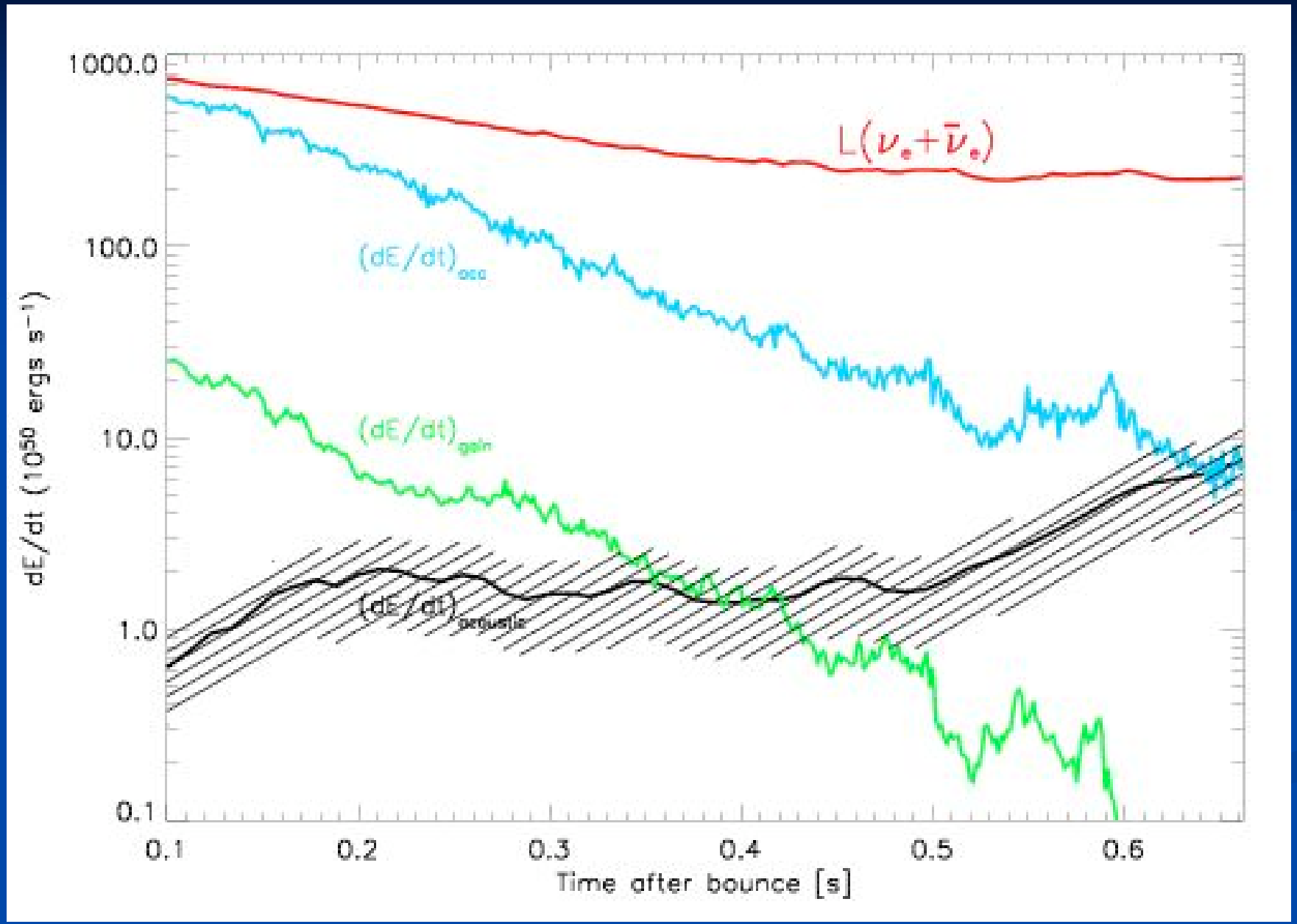


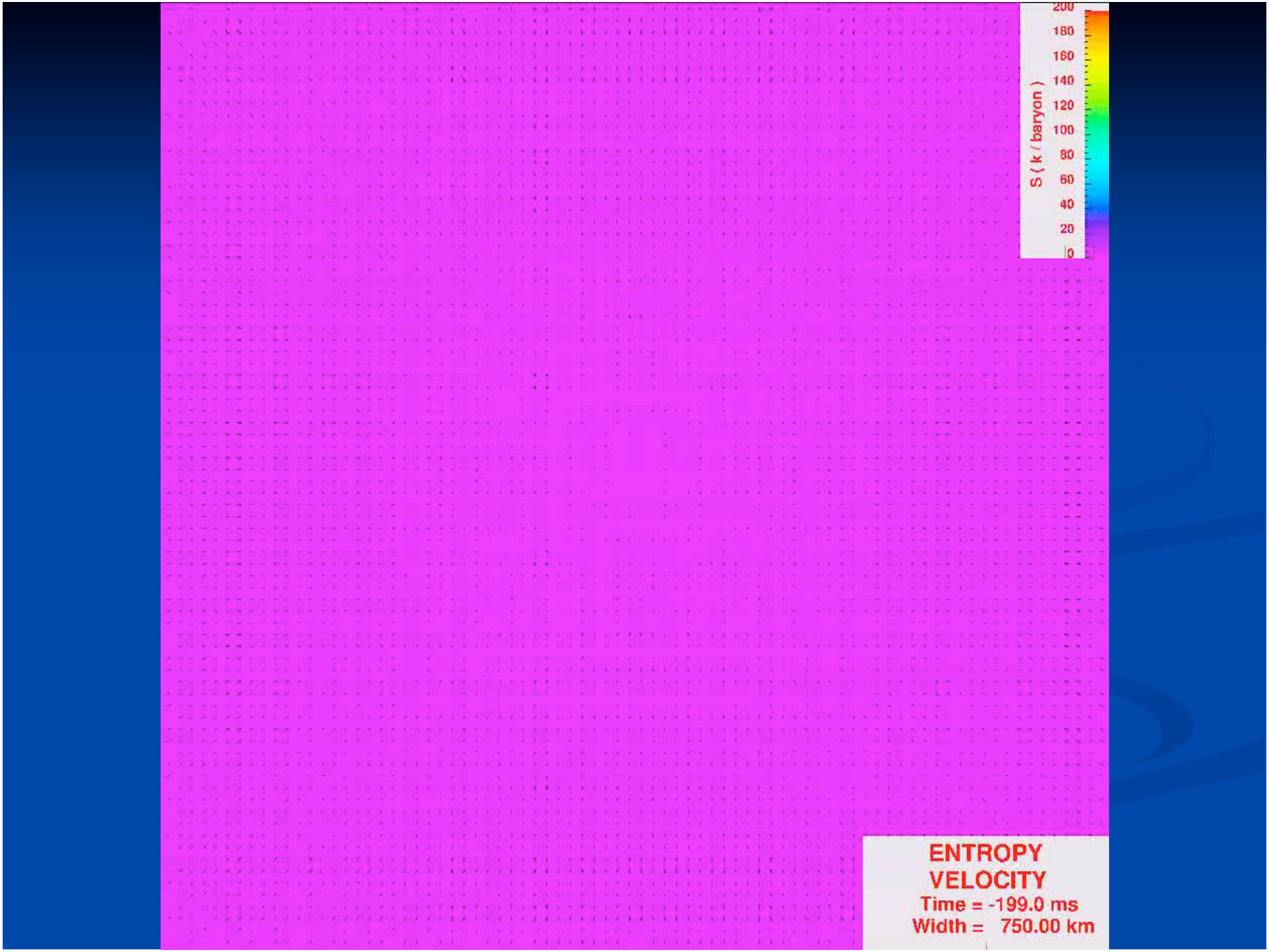


Frequency-Time Evolution of Pulsating Core at 30 km



Power Comparisons: 11 Solar-Mass model




200
180
160
140
120
100
80
60
40
20
0
S (k / baryon)
ENTROPY
VELOCITY
Time = -199.0 ms
Width = 750.00 km

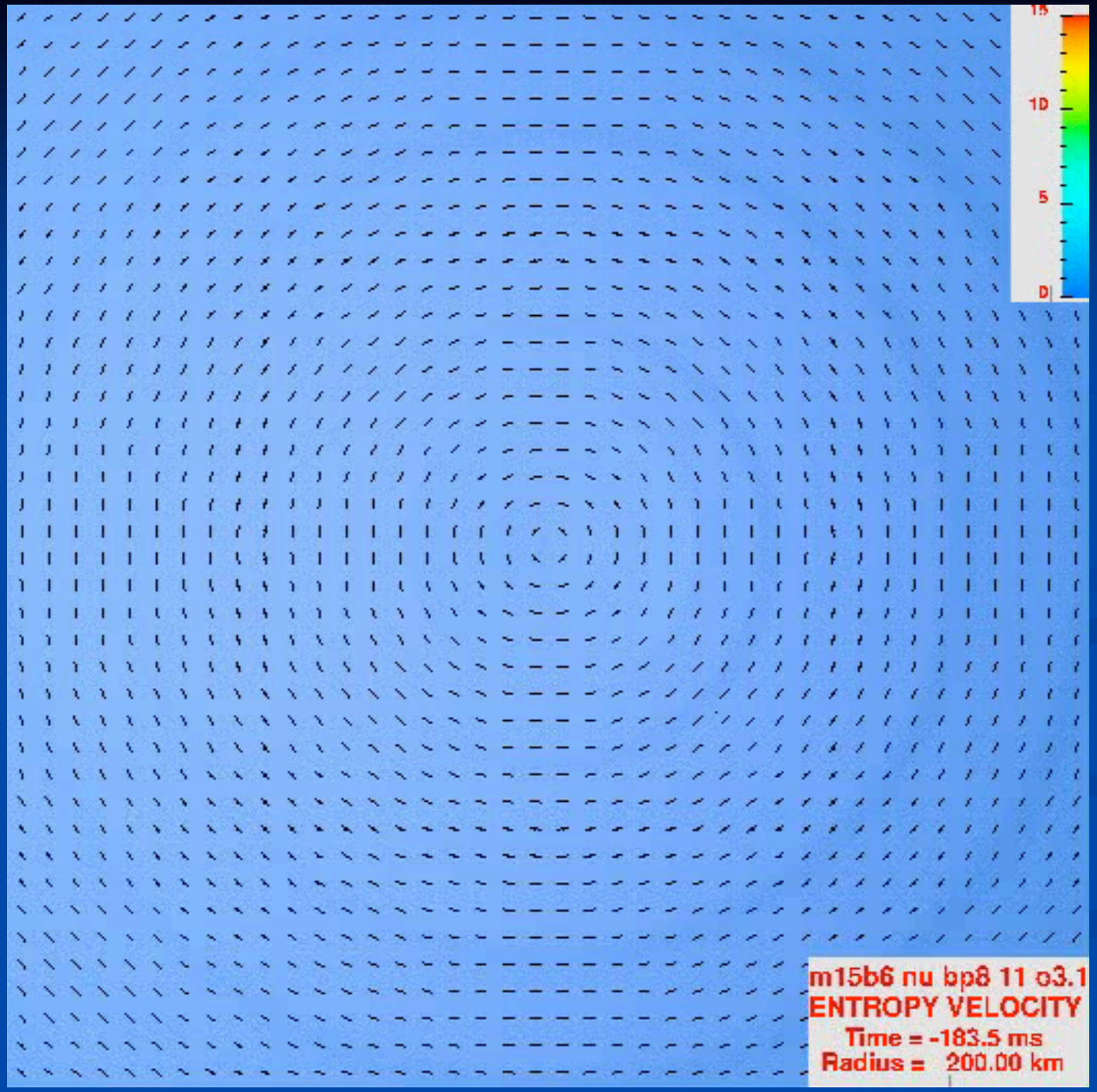
Key Features of Acoustic Mechanism

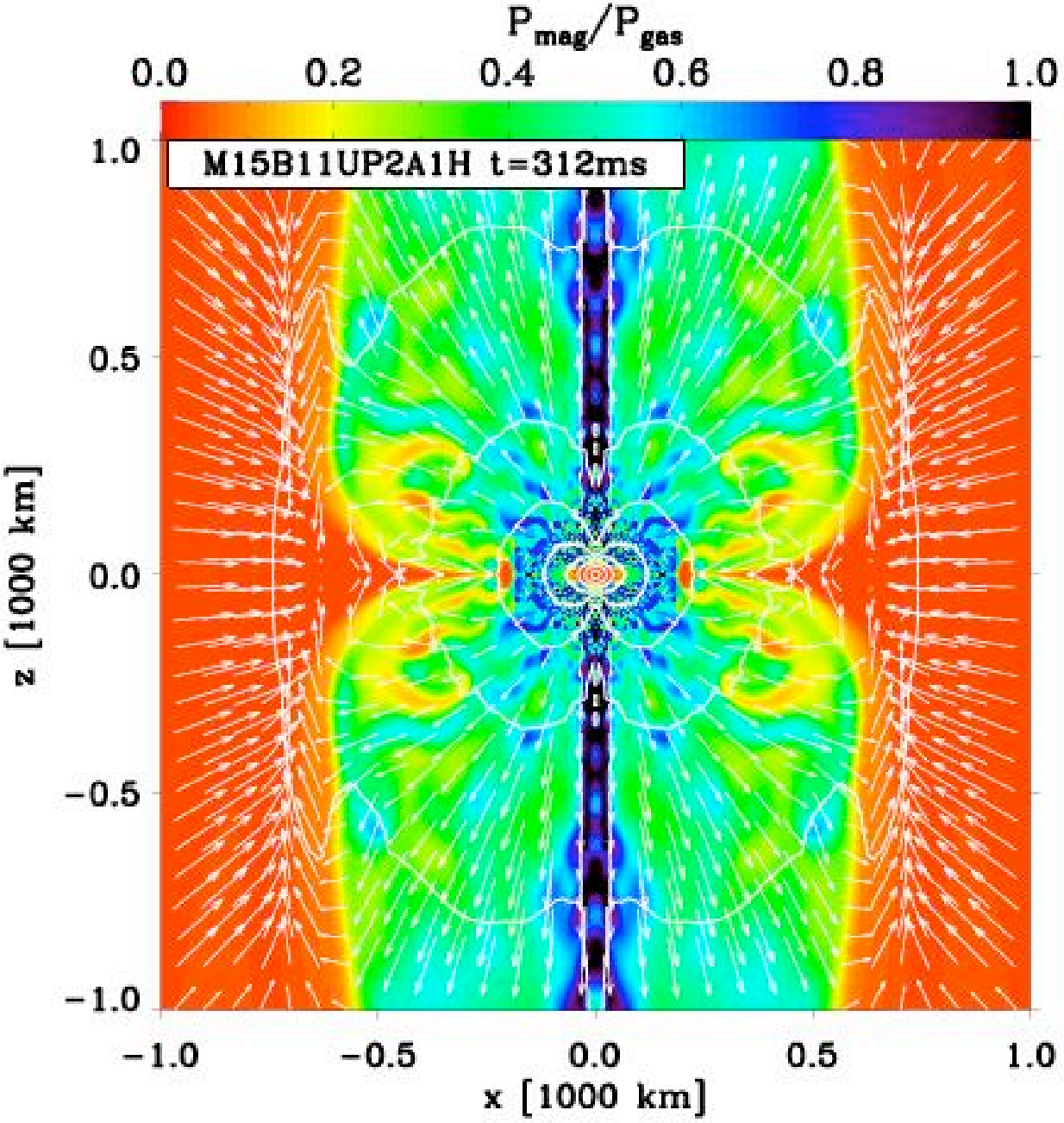
- "A Tale of Two Instabilities"
- Shock Instability (SASI) after bounce (30-80 Hz)
- Rapid core oscillation progressively excited: l=1 g-mode (~300 Hz), first by turbulence (that grows with time), then non-linearly by anisotropic downflowing plumes/streams
- Core oscillation generates sound waves that propagate outward
- Acoustic power and momentum explode the star
- Hybrid acoustic/neutrino model?
- Self-excited oscillations (very non-linear); transducer
- All models explode, but "late" (0.5-1.0 seconds after bounce
- Fundamentally aspherical explosions: unipolar?
- R-process nucleosynthesis?
- Recoil: Natural mechanism for pulsar kicks?

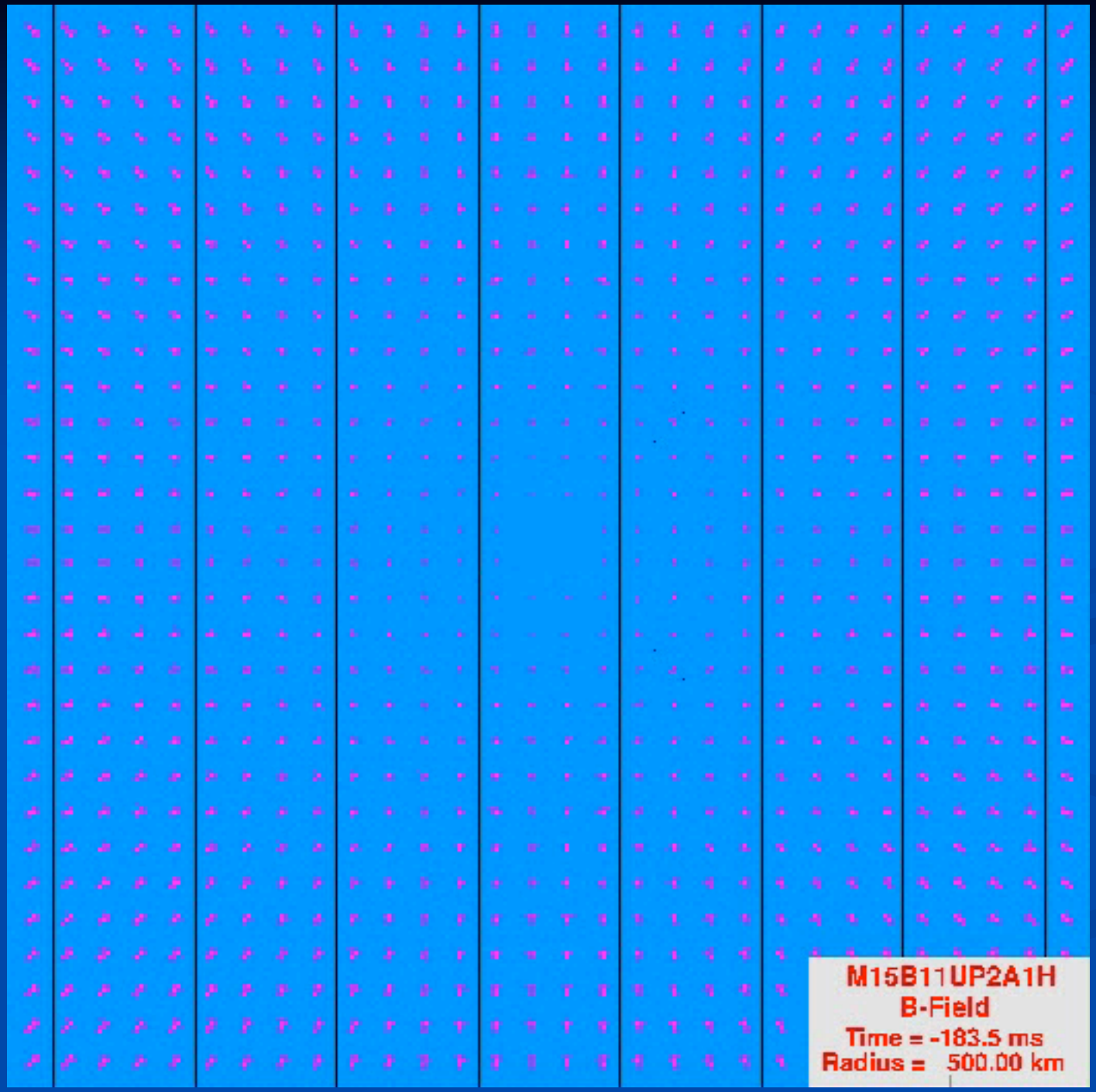
MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation

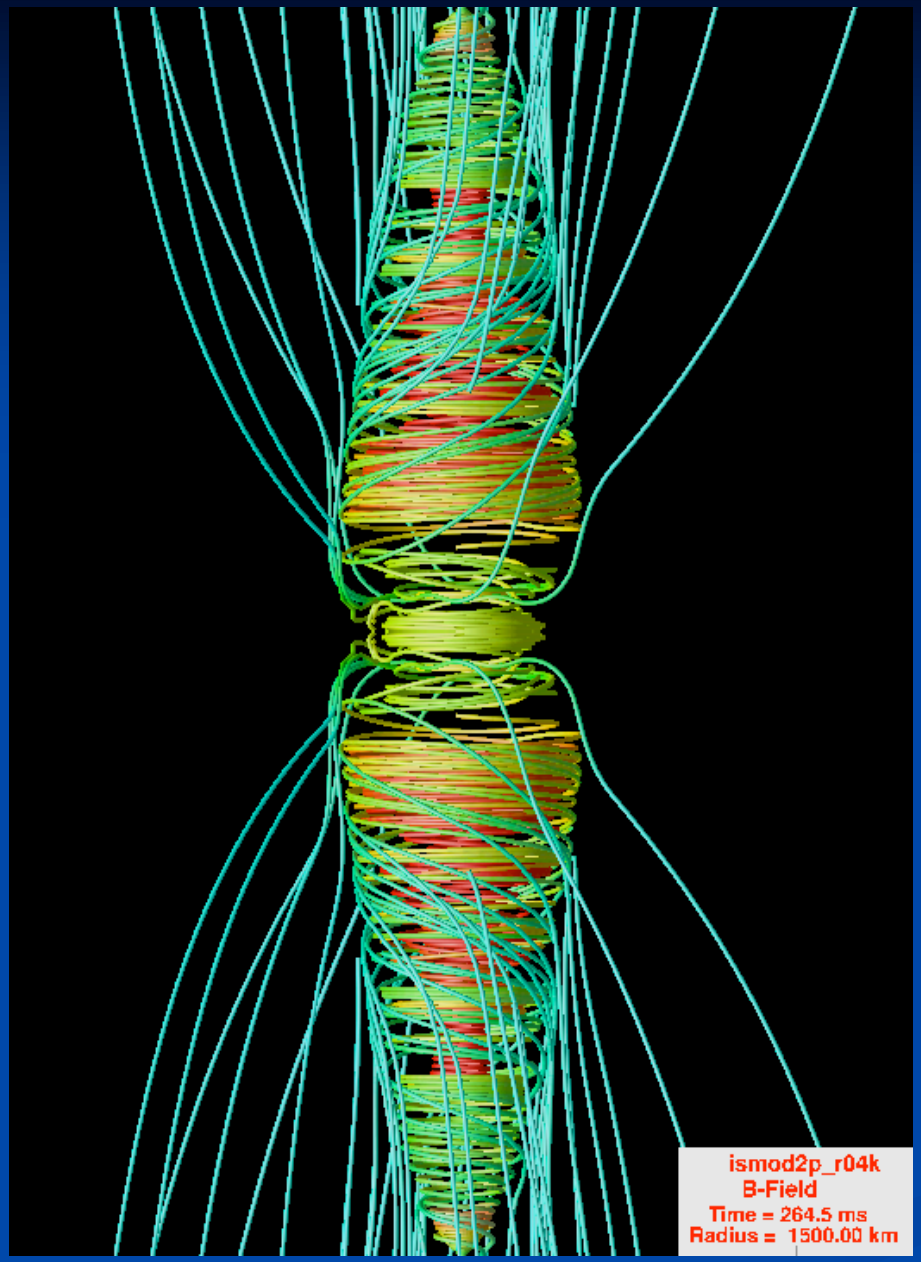
Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

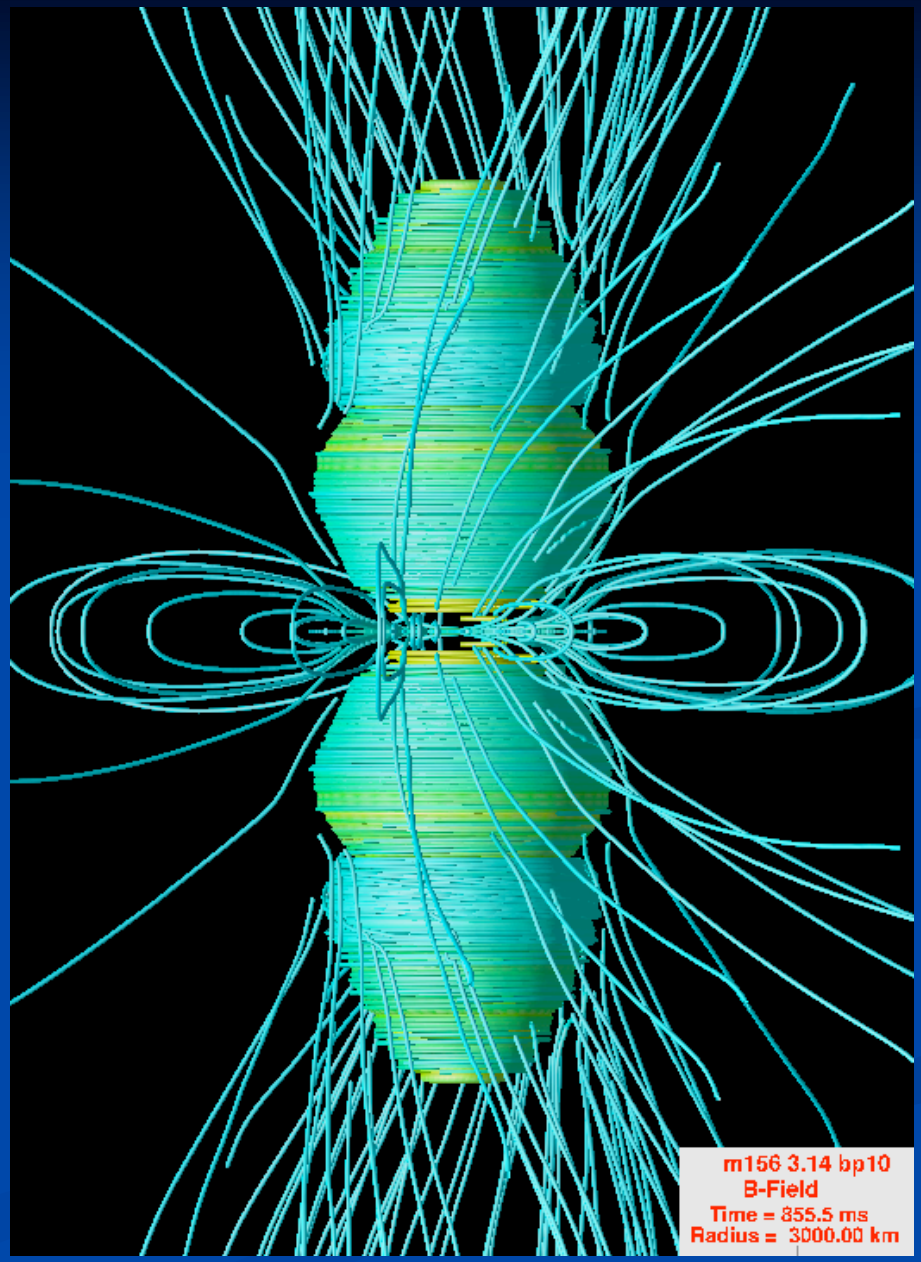
Rotation Winding, the MRI and B-field Stress effects

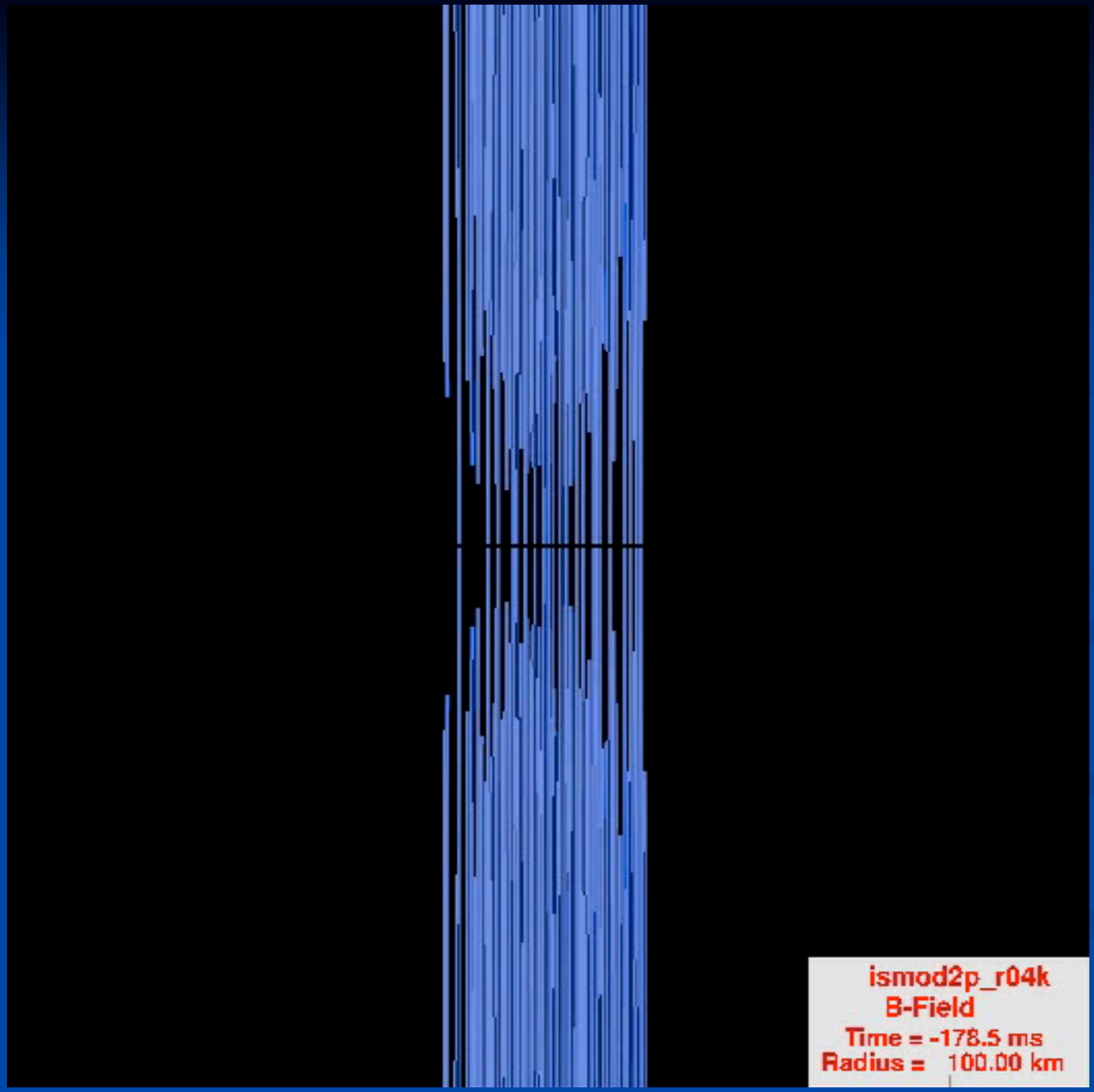

15
10
5
0
m15b6 nu bp8 11 o3.1
ENTROPY VELOCITY
Time = -183.5 ms
Radius = 200.00 km


P_{mag}/P_{gas}
0.0
0.2
0.4
0.6
0.8
1.0
M15B11UP2A1H t=312ms
1.0
0.5
0.0
−0.5
−1.0
z [1000 km]
−1.0
−0.5
0.0
0.5
1.0
x [1000 km]

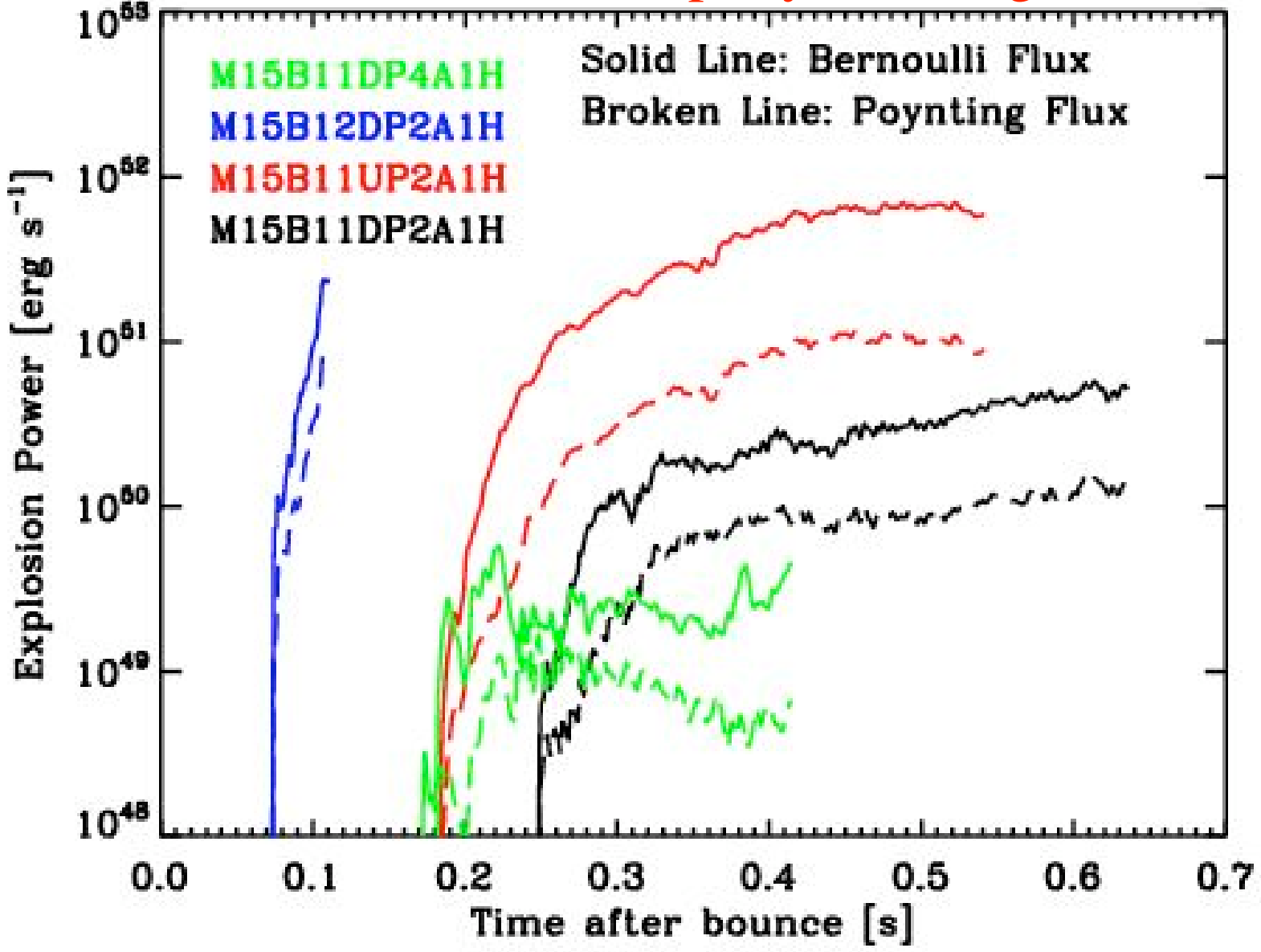

M15B11UP2A1H
B-Field
Time = -183.5 ms
Radius = 500.00 km


ismod2p_r04k
B-Field
Time = 264.5 ms
Radius = 1500.00 km


m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km


ismod2p_r04k
B-Field
Time = -178.5 ms
Radius = 100.00 km

MHD Jet Powers for Rapidly-Rotating Cores



Questions: MHD Jets

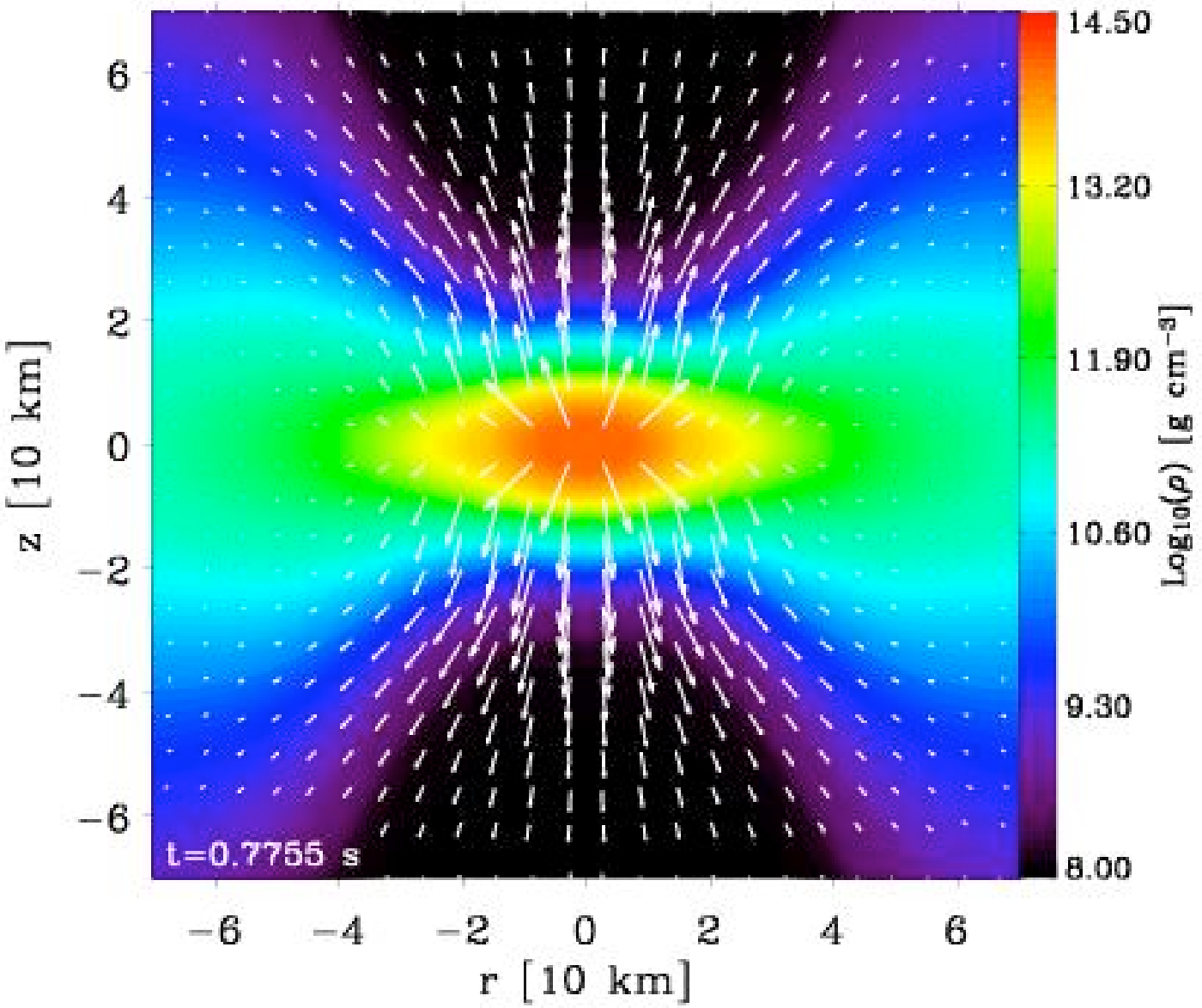
- Initial models: Spin rates and B-fields?
- 3D simulations?
- MRI?
- Dynamo?
- Whither Pulsars/Magnetars? Final spins and B-fields? Spindown?
- Hypernova/GRB connection?
- Secondary MHD Jets/low-energy explosion after other main explosion?

Neutrino Bursts/Signatures

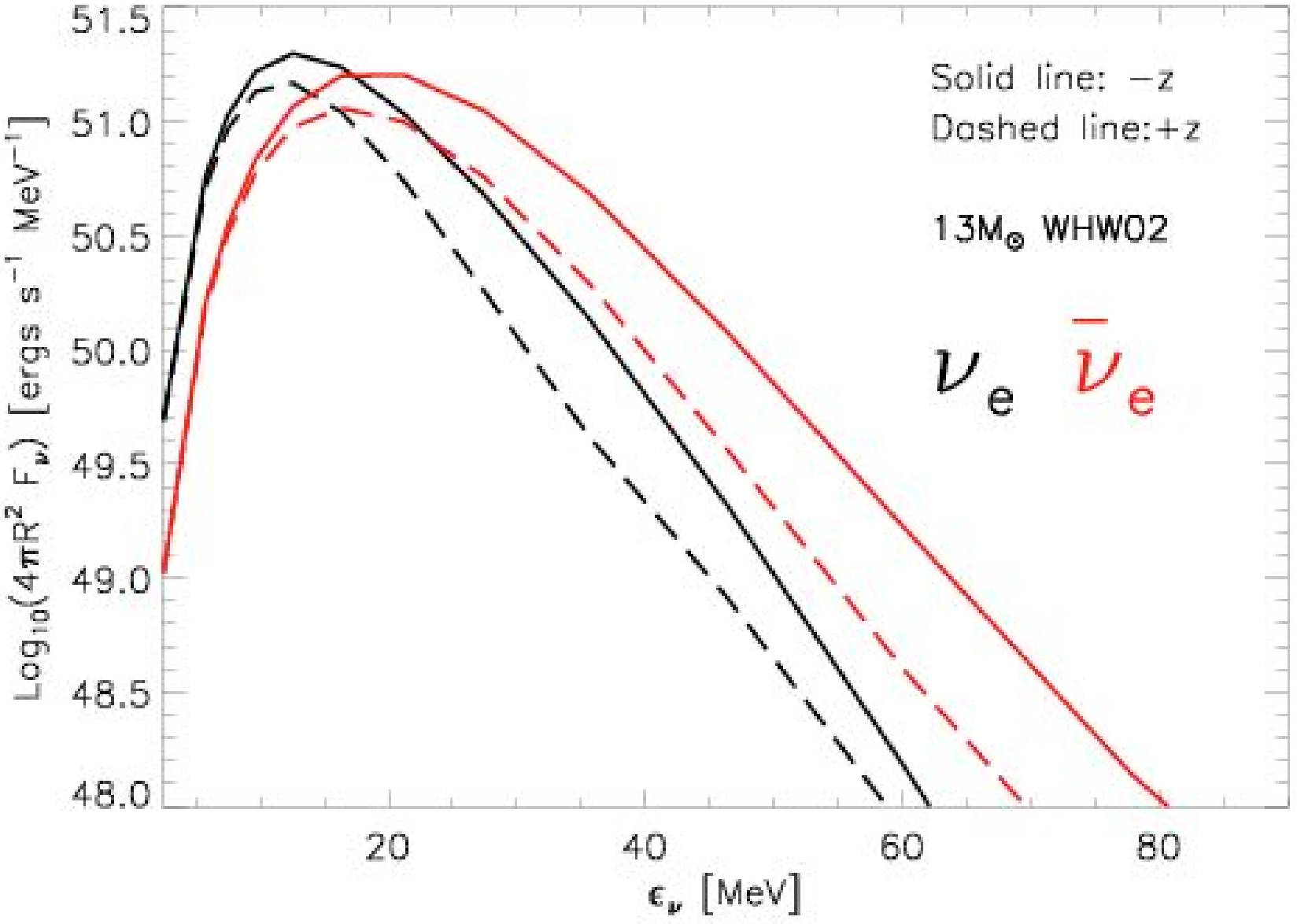
Anisotropic Neutrino Fluxes due to Rotation

2D Electron Neutrino Fluxes for 1.92 solar mass AIC model:

Rapid Rotation!

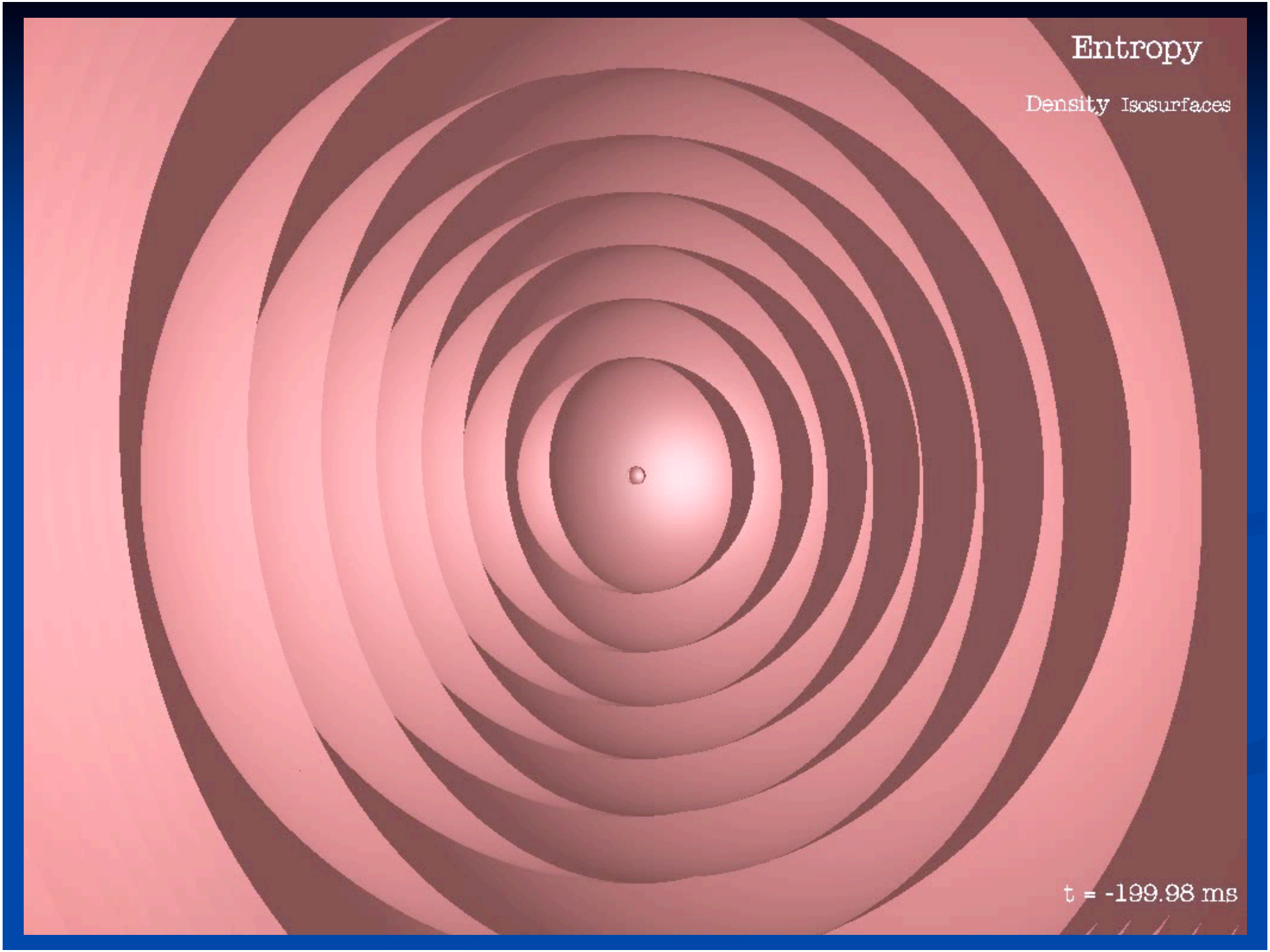


Top-Bottom Asymmetry in Neutrino Luminosity after Explosion: Kicks!



Core-Collapse Supernovae: The Future

- Numerous Explosion Mechanisms identified: Neutrino-Wind, Neutrino/SASI, Acoustic/Core-oscillation, MHD Jet, Hybrids
- Symmetry-breaking, instabilities frequently the key to explosion: Simultaneous accretion and explosion
- Multi-D (2D and 3D) radiation hydrodynamics: 3D effects?
- Is there an important role for Rotation?
- Is there a role for Magnetic fields? Pulsar/Magnetar fields?
- Viscosity? viscous heating and angular momentum transport
- Equation of state?
- Neutrino physics, rates, neutrino oscillations?
- Systematics with progenitor: kicks, r-process, SN energy, BH of observables/diagnostics?
- GRB/hypernova/SN connections!


Entropy
Density Isosurfaces
t = -199.98 ms